Ultraboost:
Investigations into the Limits of Extreme Engine Downsizing

Dr J.W.G. Turner
Jaguar Land Rover Powertrain Research
Overview of Presentation

The Ultraboost Project
  Targets and Sizing
  3-Phase Programme

Engine Design
  Cylinder Block
  Cylinder Head and WCEM

Full-Load Performance

Fuel Economy Status
  Friction

Conclusions

How Low Can You Go?
The Ultraboost Project

• The ‘Ultraboost’ project aimed to create a highly-boosted, heavily-downsized engine to provide the torque curve and power output of the naturally-aspirated Jaguar Land Rover AJ133 5.0 litre V8 engine
• It was funded by the UK Technology Strategy Board as part of its Low-Carbon Vehicles Programme
• Dyno-based multi-cylinder engine operation formed the core of the project, with modelling used to demonstrate ~35% reduction in CO₂
  > From 296 to 192 g/km on the NEDC
  > 23% of this had to come from the engine alone
• Operation on 95 RON pump gasoline was required
• The driveability of the original V8 engine was to be maintained
• Operation at very high BMEPs was necessary throughout the wide speed range typical of a gasoline engine
Project Target – Power Curve for JLR AJ133 NA V8

283 kW / 380 bhp at 6500 rpm

515 Nm at 3500 rpm

32.4 bar

400 Nm at 1000 rpm

25.1 bar

415 Nm at 6500 rpm

26.1 bar

Very high requirements on combustion and charging systems
Used in the initial sizing of the Ultraboost engine

From vehicle modelling, we knew that we needed 23% from engine when warm...

...and this requires a 60% Downsizing Factor

Supercharged ✔ Turbocharged ● Poly. (Supercharged) — Poly. (Turbocharged)
3-Phase Research Program

- **PHASE 1**
  - **2010 ⇒ 2011**
  - **AJ133 V8 NA**
    - Capacity: 5.0 litre
    - Bore: 92.5 mm Stroke: 93 mm
    - Baseline with Denso EMS, then
    - Baseline with Lotus EMS

- **PHASE 2**
  - **2011 ⇒ 2012**
  - **UB100: AJ133 mule**
    - Capacity: 2.0 litre
    - Bore: 83 mm Stroke: 92 mm
    - New combustion system
    - New head, crank, conrod, piston, intake and exhaust system
    - PFI & DI, EGR, Twin CPS and DCVCP
    - Boosted by combustion air handling unit
    - Lotus EMS

- **PHASE 3**
  - **2012 ⇒ 2013**
  - **UB200: AJ133 mule**
    - As UB100 but with engine-driven boosting and EGR systems
Project Key Requirements

- **Boosting system:** deliver a boosting system capable of producing a boost pressure of up to 3.5 bar absolute
  - To achieve specific outputs of >250 Nm/litre and 142 kW/litre
  - With best-in-class transient response and minimal parasitic losses
  - To be adopted at the UB200 design level

- **Combustion system:** deliver a knock-tolerant combustion system operating at up to 130-135 bar maximum mean peak cylinder pressure
  - Without a requirement for significant compression ratio reduction, i.e. \( \geq 9.0:1 \)
  - To be proven at the UB100 design level

- **Design, develop, build and test** the concept engines
  - In two specification levels capable of withstanding the cylinder pressure

- **Prove** that the chosen technology package was capable of delivering a 35% reduction in tailpipe CO\(_2\) over the NEDC
  - Relative to an AJ133 5.0 litre V8 NA gasoline engine
  - When operating in 2013 Range Rover product versus a 2010 baseline production vehicle
Core Engine Design

• The core engine is common to both UB100 and UB200
  > Effectively the UB100 engine was the basis of UB200

• The project was structured so that changes could be made between Phases 2 and 3 if necessary
  > However, UB100 was extremely reliable, and met initial performance and economy targets, so this was not done

• UB100 used a JLR AJ133 cylinder block and pumps as base, with a new head and measures to reduce the swept volume of the ‘half engine’
  > Because the architecture would be suitable to accept the loadings that would be applied to it

• As a consequence of this ‘design for reliability’ decision, its friction was high
  > Will return to this later
Cylinder Block

- **Cylinder block** is a modified AJ133 V8 unit
  - Fitted with a flat-plane crankshaft and siamesed liner pack to reduce bore
  - Uses the standard water, oil and HP fuel pumps, main bearings, fuel rail etc.
Cylinder Head and WCEM

- **Cylinder head** is completely new
  - Retains the fast-acting dual cam phasers and chain drive from AJ133 donor
  - Uses ‘Thumper Cams’ to generate actuating torque
  - B bank is blanked off and the coolant flow is bypassed (also via water-cooled exhaust manifold or WCEM)
ENGINE TESTING AND RESULTS

All data reported in this presentation is taken with 95 RON pump gasoline and at Lambda = 1 operation unless otherwise stated.

Preignition is essentially absent.
A variety of tests were conducted with UB100 during Phase 2

Di/PFI split ratio tests showed only a declining torque output as fuel was biased towards PFI

> Believed to be indicative of excellent homogenization and high charge motion

> Loss of charge-air cooling and oxygen displacement increased with PFI
Engine Torque versus DI/PFI Split

Fixed Valve Timing:
Exhaust MOP = 96° BTDC
Inlet MOP = 88° ATDC

DI/PFI Loop at 2000 rpm
WOT – $P_{Ma}$ 2.2 bar Abs.

Increasing % PFI showed a large drop in torque and stability

Believed to be indicative of very good mixing from the port geometry versus oxygen displacement with PFI

Increasing PFI %

Torque / [Nm]

Spark Advance / [btcd]
UB100 Testing during Phase 2

- Comprehensive EGR tests were carried out
  - Including catalyzed versus uncatalyzed tests
  - To be reported by the University of Bath elsewhere

- A large matrix of fuels was tested as part of a fuels properties test
  - Decoupled RON and MON, ‘size of the prize’ octane, oxygenates and high alcohol contents, including gasoline-ethanol-methanol mixtures (GEM fuels)
  - To be reported by Shell elsewhere

- Constant air density tests were also conducted at 1500 rpm
  - To help assess the value of higher-effectiveness charge cooling techniques
    - Including turboexpansion
Constant Air Density Testing

Tests conducted at 1500 rpm

Effect is linear despite heavy non-linearity of heat transfer and combustion kinetics

Knock-Limited Spark Advance / [BTDC]

1.67 kg/m³

2.01 kg/m³

2.34 kg/m³

Inlet Manifold Temperature / [degC]

1.67 kg/m³

2.01 kg/m³

2.34 kg/m³
At the end of the UB100 testing in Phase 2 the engine was operated with the selected turbocharger only

- As part of a scoping test to check where the turbocharger run-up curve met the torque curve

For this a simple test-bed pipe system was installed together with the vehicle exhaust system

- The test-bed air-to-water heat exchanger was used, being operated to achieve representative plenum temperatures

The engine could meet the target torque curve from 3000 rpm and exceeded the peak torque and power targets

- These project targets were therefore met during Phase 2
UB100 with WCEM and GT30

Conditions for turbocharger run-up performance line:

- $\lambda = 0.9$
- $\lambda = 1$
- 10% EGR

524 Nm
382 bhp

Torque / [Nm]

Engine Speed / [rpm]

- AJ133 Baseline
- UB100 on Boost Rig
- UB100 using Engine-Driven Turbocharger
The UB200 engine was assembled, fitted to the test cell at the University of Bath and tested as a self-contained unit for the first time.

> At the end of the project a compound curve was available, with detailed data up to 4750 rpm having been taken

A modification to the supercharger drive ratio was necessary, since its interaction with the turbocharger was not as strong as hoped for, resulting in a slight miss on the low-speed torque target.

> Various countermeasures are being tested to address this

Imperial College have since started investigations into this, with some interesting findings as to what happens when air inlet conditions into the supercharger are changed.
**Exceeding the torque target above 1500 rpm has proved straightforward**

**Peak torque and power targets have been met**

**Minimum BSFC <250 g/kWh**

The engine has been operated at 550 Nm (~35 bar)

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Peak torque and power targets have been met.
FINAL UB200 FUEL ECONOMY STATUS
Fuel Consumption Status

• 15 minimap points were optimized covering ~99% of fuel used on NEDC
• The project fuel consumption monitor spreadsheet suggested 15% better fuel consumption when warm

<table>
<thead>
<tr>
<th>Minimap Point</th>
<th>Engine Speed (rpm)</th>
<th>Brake Torque (Nm)</th>
<th>BSFC (g/kWhr)</th>
<th>BSFC relative to AJ133 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>600</td>
<td>27.9</td>
<td>482.4</td>
<td>-35.0</td>
</tr>
<tr>
<td>2</td>
<td>1500</td>
<td>39.8</td>
<td>355.1</td>
<td>-29.0</td>
</tr>
<tr>
<td>3</td>
<td>1500</td>
<td>104.2</td>
<td>257.7</td>
<td>-13.7</td>
</tr>
<tr>
<td>4</td>
<td>1500</td>
<td>198.9</td>
<td>248.1</td>
<td>-0.3</td>
</tr>
<tr>
<td>5</td>
<td>2000</td>
<td>79.6</td>
<td>275.2</td>
<td>-18.8</td>
</tr>
<tr>
<td>6</td>
<td>2000</td>
<td>198.6</td>
<td>239.3</td>
<td>-4.4</td>
</tr>
<tr>
<td>7</td>
<td>1250</td>
<td>15.9</td>
<td>614.5</td>
<td>-38.1</td>
</tr>
<tr>
<td>8</td>
<td>1000</td>
<td>15.9</td>
<td>612.9</td>
<td>-36.8</td>
</tr>
<tr>
<td>9</td>
<td>1000</td>
<td>79.6</td>
<td>278.5</td>
<td>-17.2</td>
</tr>
<tr>
<td>10</td>
<td>1250</td>
<td>159.2</td>
<td>246.7</td>
<td>-6.1</td>
</tr>
<tr>
<td>11</td>
<td>1350</td>
<td>238.7</td>
<td>260.5</td>
<td>6.4</td>
</tr>
<tr>
<td>12</td>
<td>1500</td>
<td>298.4</td>
<td>273.9</td>
<td>14.7</td>
</tr>
<tr>
<td>13</td>
<td>1250</td>
<td>119.4</td>
<td>254.5</td>
<td>-10.7</td>
</tr>
<tr>
<td>14</td>
<td>1250</td>
<td>59.7</td>
<td>294.6</td>
<td>-24.7</td>
</tr>
<tr>
<td>15</td>
<td>1500</td>
<td>139.3</td>
<td>247.4</td>
<td>-8.4</td>
</tr>
</tbody>
</table>

Weighted overall reduction on NEDC = **15.02%**
Fuel Consumption Status

• Setting the idle fuel consumption to 0% - originally as a limit case for stop-start - showed that the warm fuel consumption improvement increased to 23%
  > Clearly, idle fuel consumption was still very important, despite the benefits of downsizing
  > But stop-start is a vehicle-level benefit, so this any improvement could not be attributed to the engine
• However, an immediate observation is that friction would similarly be important
• Friction was therefore measured and found to be very high
  > Because of its AJ133 parentage, the engine has two DI pumps, full V8 water and non-adjustable oil pumps, large main bearings etc.
UB200 Measured Friction

FEV friction scatter band for 4-cylinder boosted engines
• When friction is accounted for, the engine achieves the target fuel consumption improvement
  > 23.8% for no second-order balancing and 600 rpm idle, reducing to 22.6% for full second-order balancing and 680 rpm idle
• A full vehicle fuel consumption modelling exercise has been completed using CalSim, investigating the NEDC, FTP-75 and 120 km/h cruise
  > Using the second-order balancing and 680 rpm idle data

<table>
<thead>
<tr>
<th></th>
<th>NEDC CO₂ Delta (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013 MY Range Rover with AJ133 NA V8</td>
<td>8.3</td>
</tr>
<tr>
<td>Stop-start</td>
<td>7.6</td>
</tr>
<tr>
<td>UB200</td>
<td>21.0</td>
</tr>
<tr>
<td>Total</td>
<td>36.9</td>
</tr>
</tbody>
</table>

Vehicle measures between 2010 and 2013 MY Range Rover include stop-start, 420 kg weight reduction, 8- v 6-speed gearbox, improved aero and reduced driveline friction

36.9% FE benefit over AJ133 when friction is adjusted and warm-up profile is as per industry current standard – exceeds the project target

Less than 23% because of warm-up
Vehicle FE (CalSim Modelled)

<table>
<thead>
<tr>
<th></th>
<th>120kph Cruise l/100km Delta (%)</th>
<th>120kph Cruise mpg Delta (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013 MY Range Rover with AJ133 NA V8</td>
<td>18.4</td>
<td>22.6</td>
</tr>
<tr>
<td>Stop-start</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>UB200</td>
<td>6.1</td>
<td>9.9</td>
</tr>
<tr>
<td>Total</td>
<td>24.5</td>
<td>32.5</td>
</tr>
</tbody>
</table>
The Downsizing Effect...

200 Nm at 1500 rpm = 31.4 kW
200 Nm at 2000 rpm = 41.9 kW
## Combustion Chamber Considerations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>AJ133</th>
<th>Ultraboost</th>
<th>Ultraboost to AJ133 Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression ratio (:1)</td>
<td>11.5</td>
<td>9.0</td>
<td>-21.7</td>
</tr>
<tr>
<td>Combustion chamber volume per cylinder (cm³)</td>
<td>59.51</td>
<td>62.22</td>
<td>4.6</td>
</tr>
<tr>
<td>Combustion chamber surface area per cylinder (mm²)</td>
<td>16,077</td>
<td>13,934</td>
<td>-13.3</td>
</tr>
<tr>
<td>Surface area to volume ratio (cm⁻¹)</td>
<td>2.70</td>
<td>2.24</td>
<td>-17.1</td>
</tr>
<tr>
<td>Combustion chamber surface area for whole engine (mm²)</td>
<td>128,616</td>
<td>55,736</td>
<td>-56.7</td>
</tr>
<tr>
<td>Top land crevice volume (mm³)</td>
<td>428</td>
<td>370</td>
<td>-13.6</td>
</tr>
</tbody>
</table>

*Surface area-to-volume ratio for Ultraboost is 17.1% lower than for AJ133*

*Otto cycle demerit due to the 21.7% drop in CR from 11.5:1 to 9:1 is only 6.2%*
SUMMARY AND CONCLUSIONS
Summary and Conclusions (1)

• The ‘Ultraboost’ project aimed to create a 2.0 litre downsized engine to provide the torque curve and power output of the JLR NA 5.0 litre V8
  > 515 Nm at 3500 rpm and 283 kW / 380 bhp at 6500 rpm
  > Target was a 35% improvement in vehicle-level fuel economy
• It was part-funded by the UK Technology Strategy Board as part of its Low-Carbon Vehicles Programme
• Performance targets were met, except below 1500 rpm
• The engine proved to be extremely reliable and resistant to preignition, and its knock limit was high
• All testing reported here was carried out with 95 RON pump gasoline
  > Good fuel consumption and low exhaust temperatures were achieved even without cooled EGR
Summary and Conclusions (2)

- The project achieved a measured 15% improvement in fuel consumption from data recorded on the UB200 engine
  - Against a 23% requirement
- However, friction has been measured and found to be high
- A walk to a theoretical state-of-the-art 4-cylinder engine resulted in the achievement of the fuel consumption target
- ‘Modelled’ vehicle fuel economy exceeded the project target
- From the results gathered, the limit to extreme downsizing appears to be with the charging system and not the combustion system
- This has been an extremely successful collaborative research project – our thanks go to all the other partners and to the UK Technology Strategy Board for supporting it

However, one major question remains unanswered…
How Low Can You Go?

Data from McAllister and Buckley, 2009

Used in the initial sizing of the Ultraboost engine

Moving to DF = 70% gives another 6%...

…but where is the limit?

We still don’t know

Downsizing to 100% implies a gas turbine

100% reduction implies broken 2nd Law of Thermodynamics

Supercharged

Turbocharged

Poly. (Supercharged)

Poly. (Turbocharged)
For more information see SAE paper 2014-01-1185, “Ultra Boost for Economy: Extending the Limits of Extreme Engine Downsizing”

THANK YOU FOR LISTENING